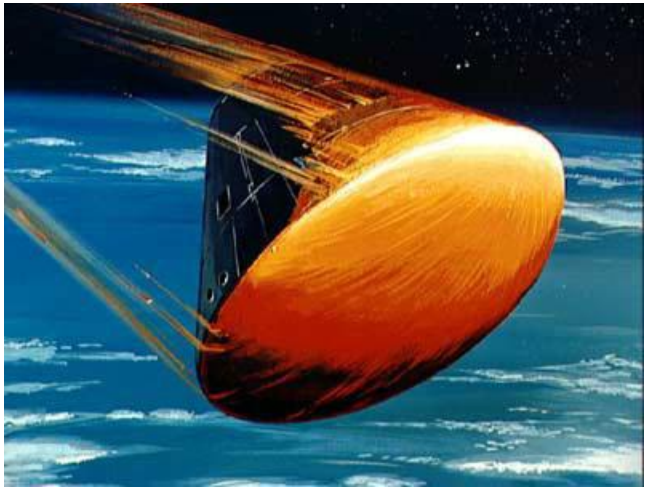
Ablative Thermal Protection System (TPS) Margin Study



An artist's rendering of the Apollo command module's re-entry into the Earth's atmosphere

Steven Rickman (NASA JSC)

Lawrence Green (NASA LaRC)*

Brian Remark (NASA JSC)

Stan Bouslog (NASA JSC)

Jeremy Vander Kam (NASA ARC)

Mohammad Khalessi (PredictionProbe, Inc.)

*Vehicle Analysis Branch (E401)

NASA Langley Research Center (LaRC)

Hampton, VA 23681

lawrence.l.green@nasa.gov

Outline

- Objectives
- Possible Data Sources
- Trajectories
- Assumptions and Considerations
- Computational Tools and Techniques
- Ablation Overview
- Design of Experiments
- Reliability Assessment
- Conclusions

Objectives

1. Provide input to a planned arc jet testing campaign
   – Use **Design of Experiments (DOE)**

2. Assess the TPS reliability using the **bondline temperature**
   – Use **Uncertainty Quantification (UQ)**
   – Use **Probabilistic Technology (PT)**

Temperature at the junction of ablative material to the carrier structure

3. Provide sensitivity inputs to the TPS margin and design process
   – Use **UQ** and **PT**
   – Not discussed in this presentation

Possible Data Sources

- Mission trajectory test flight(s)
  - **Extremely limited and expensive**
  - Continuously varying 3-D environmental conditions (from benign to ablative)
  - Mixture of laminar, transitional and turbulent flows

- Arc Jet experimental testing (NASA Ames and NASA Johnson)
  - **Small sample size** (30) testing of sample materials
  - **Facility limitations**
  - **Axisymmetric approximation** of discrete ablative conditions
  - Extended durations of **laminar flow**

- Mission trajectory computational simulations
  - Essentially infinite sample sizes
  - **1-D approximation** of discrete or varying ablative behaviors
  - Usually modeled as fully turbulent flows (conservative assumption)

Trajectories

1. High heat flux
   - 2009–era focus mission
   - Most of existing data
2. **Intermediate heat flux**
   - 2011 primary mission
   - Limited existing data
3. **Low heat flux / high heat load**
   - 2011 secondary mission
   - Essentially no existing data

Focus for current work: DOE and Reliability Assessment

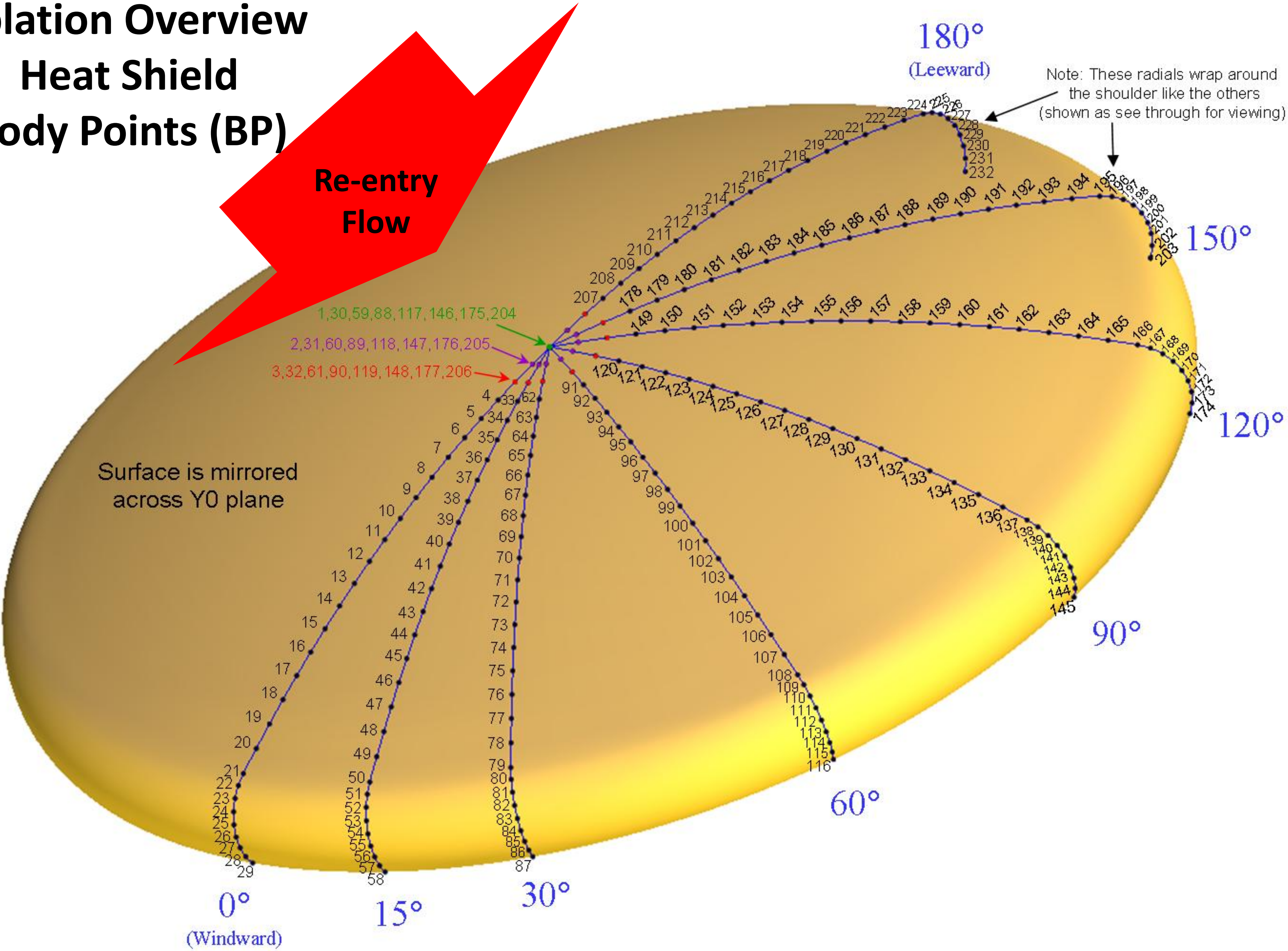
Assumptions and Considerations

- Use existing aerothermal test data and computational code
  - **Large reproducibility uncertainty for existing test data**
  - **Key metric (bondline temperature) was not measured within the existing data**
  - Few and highly uncertain test / computation comparisons
  - Model form correction term uncertainty
- Consider material property variations
  - 11 possible material variations within the computational code
  - Limited measured data available
  - **No measured data for most of the possible material variations**
- Reliability failure criterion
  - Not defined ***a priori***
  - Team defined "best guess" failure criterion as the work progressed
  - **Consider a few failure criterion variants to determine the robustness of the reliability estimates**

Computational Tools and Techniques

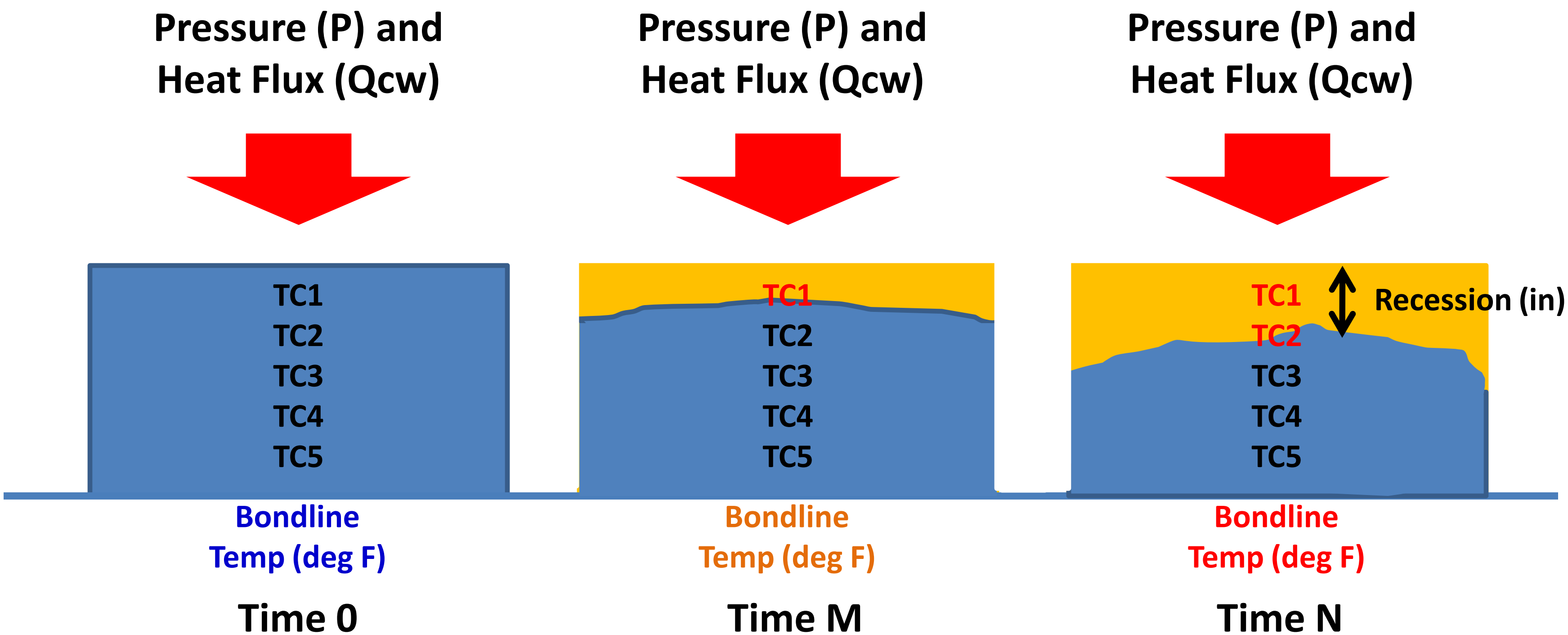
- STAB: aerothermal computational simulation code
- General statistical analysis (Microsoft Excel)
- DOE and UQ
  - Analysis of Variance (ANOVA) statistical technique
  - **Design-Expert (DX8) software from Stat-Ease, Inc.**
  - D-Optimal DOE proposed to maximize the information returned
- Uncertainty Propagation via probabilistic methods:
  - Monte Carlo Simulation (MCS) implemented by Green within **UNIPASS software from PredictionProbe, Inc.**
    - **"Low" fidelity reliability assessment implementation**
    - **Baseline and alternative failure criteria (described subsequently)**
  - First-Order Reliability Methods (FORM) implemented (under contract) within **SPISE software from PredictionProbe, Inc.**
    - **"High" fidelity reliability assessment implementation**
    - **Alternative failure criteria (described subsequently)**

Ablation Overview
Heat Shield
Body Points (BP)



Ablation Overview

Arc Jet Testing Illustration



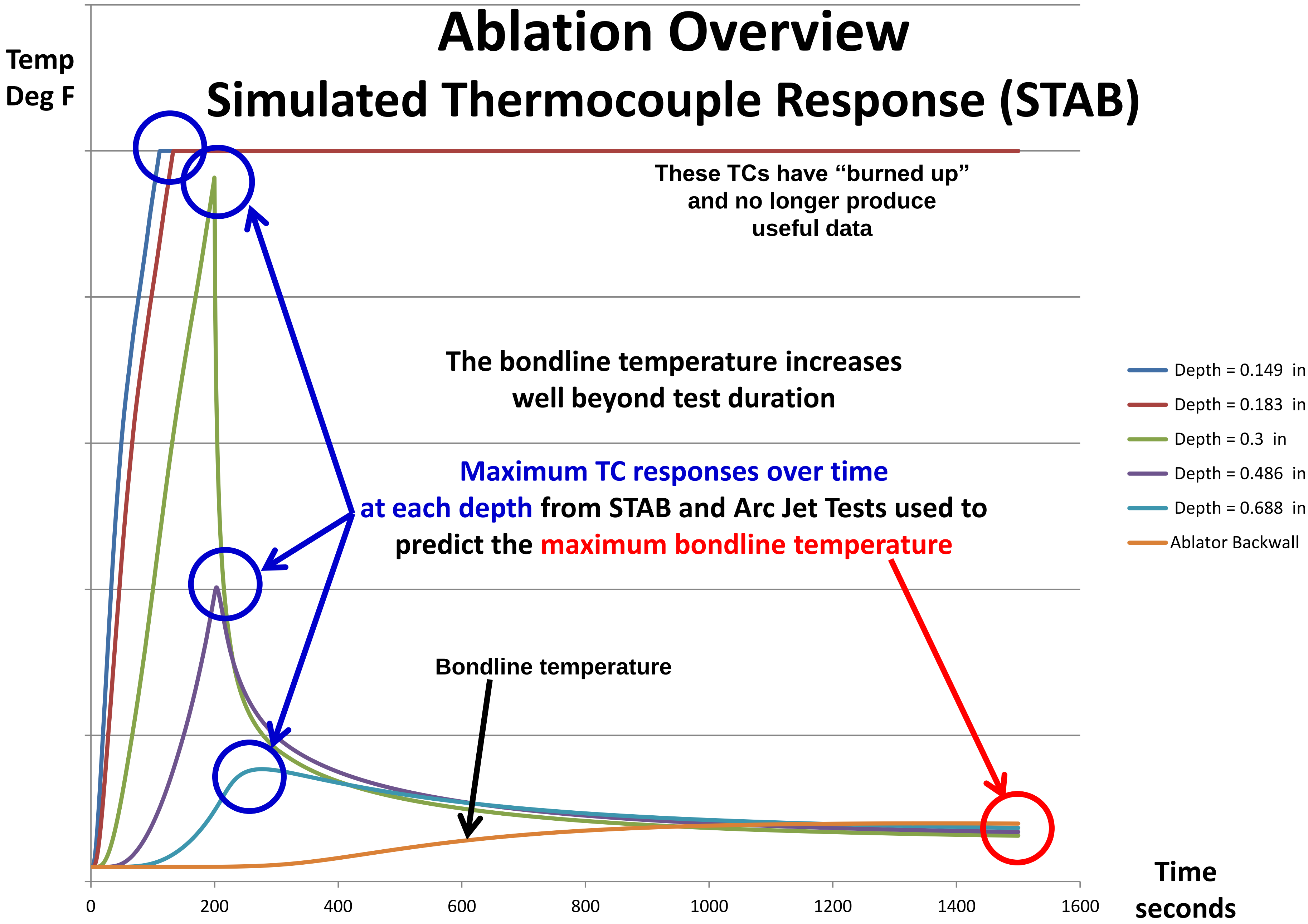
Tests are typically conducted over durations of up to 300 seconds

The bondline temperature is currently used to establish the TPS reliability.

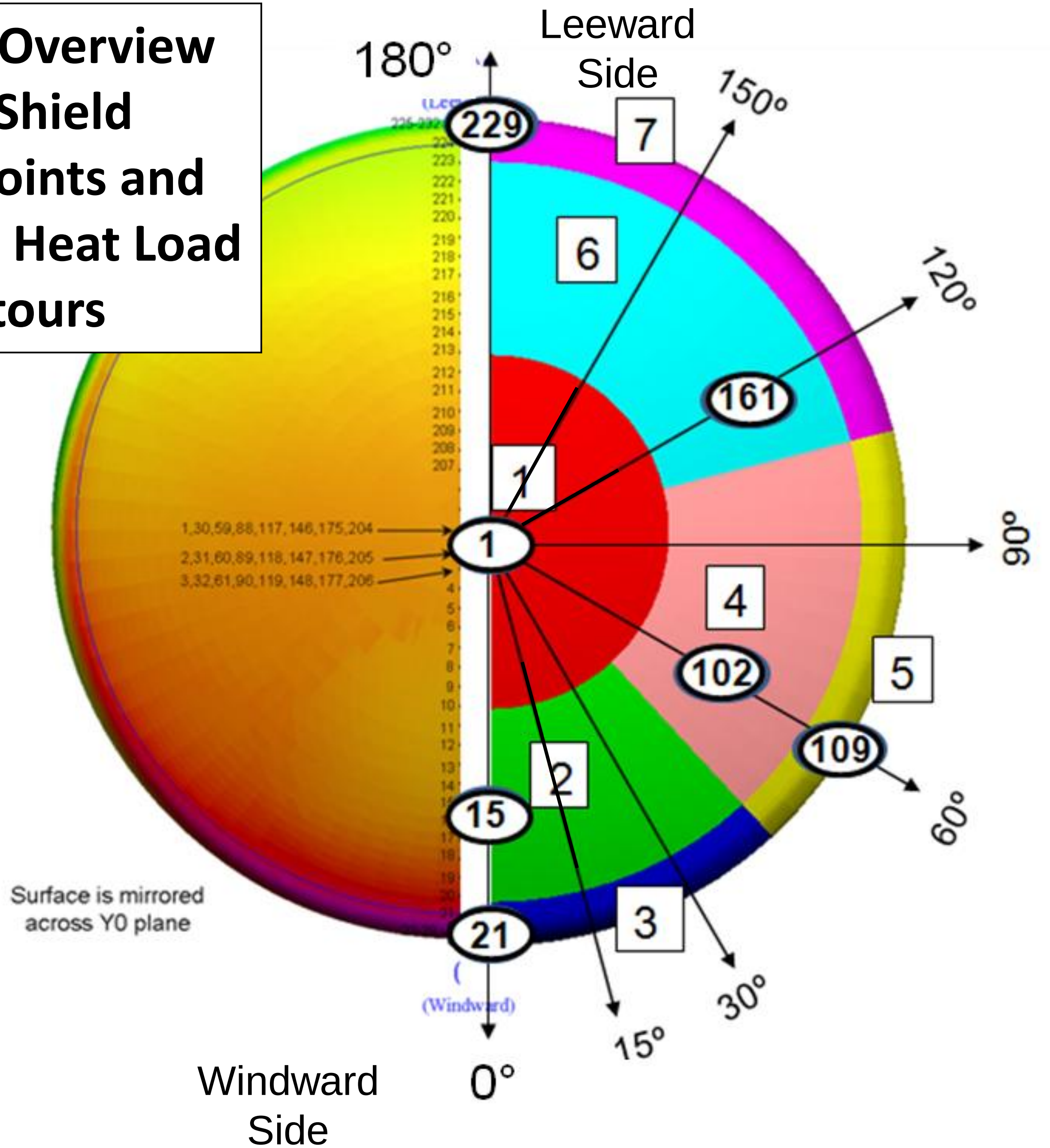
However, bondline temperature was not measured, it is only simulated.
There is considerable uncertainty in this aspect of the reliability assessment, as there were only 24 comparisons between test and computation available!

Ablation Overview

Simulated Thermocouple Response (STAB)

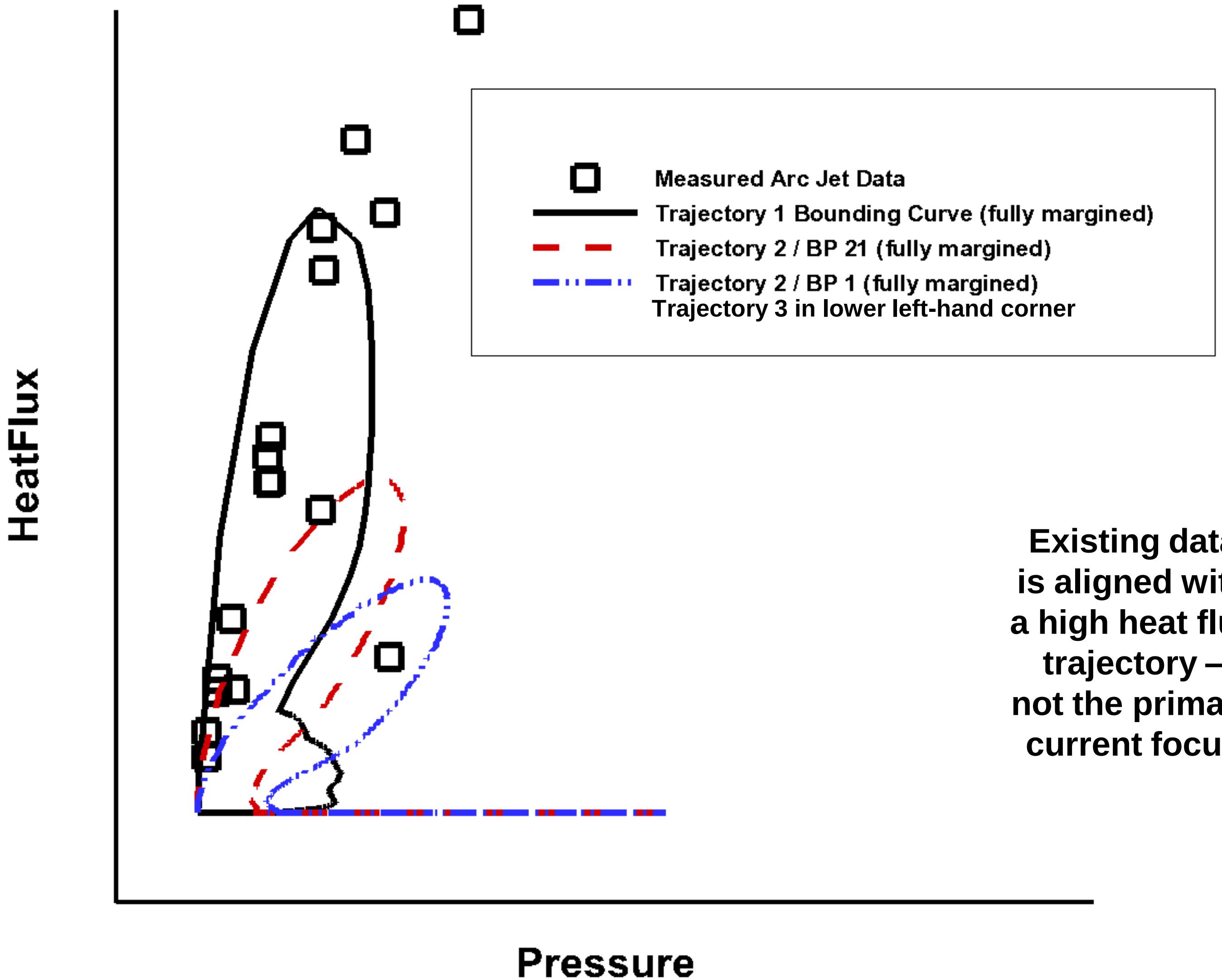


Ablation Overview Heat Shield Design Points and Integrated Heat Load Contours



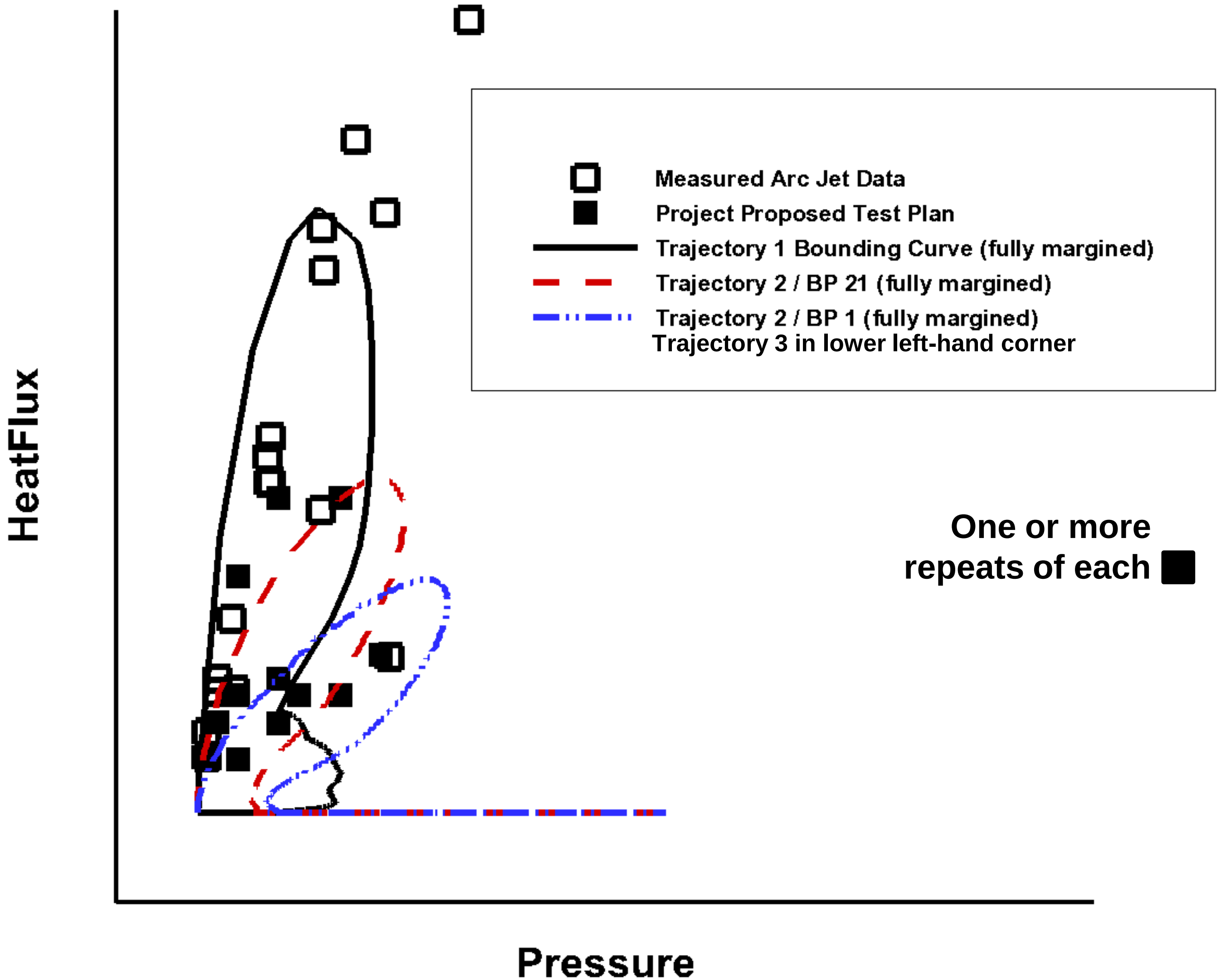
Design of Experiments

Design Of Experiments (1)



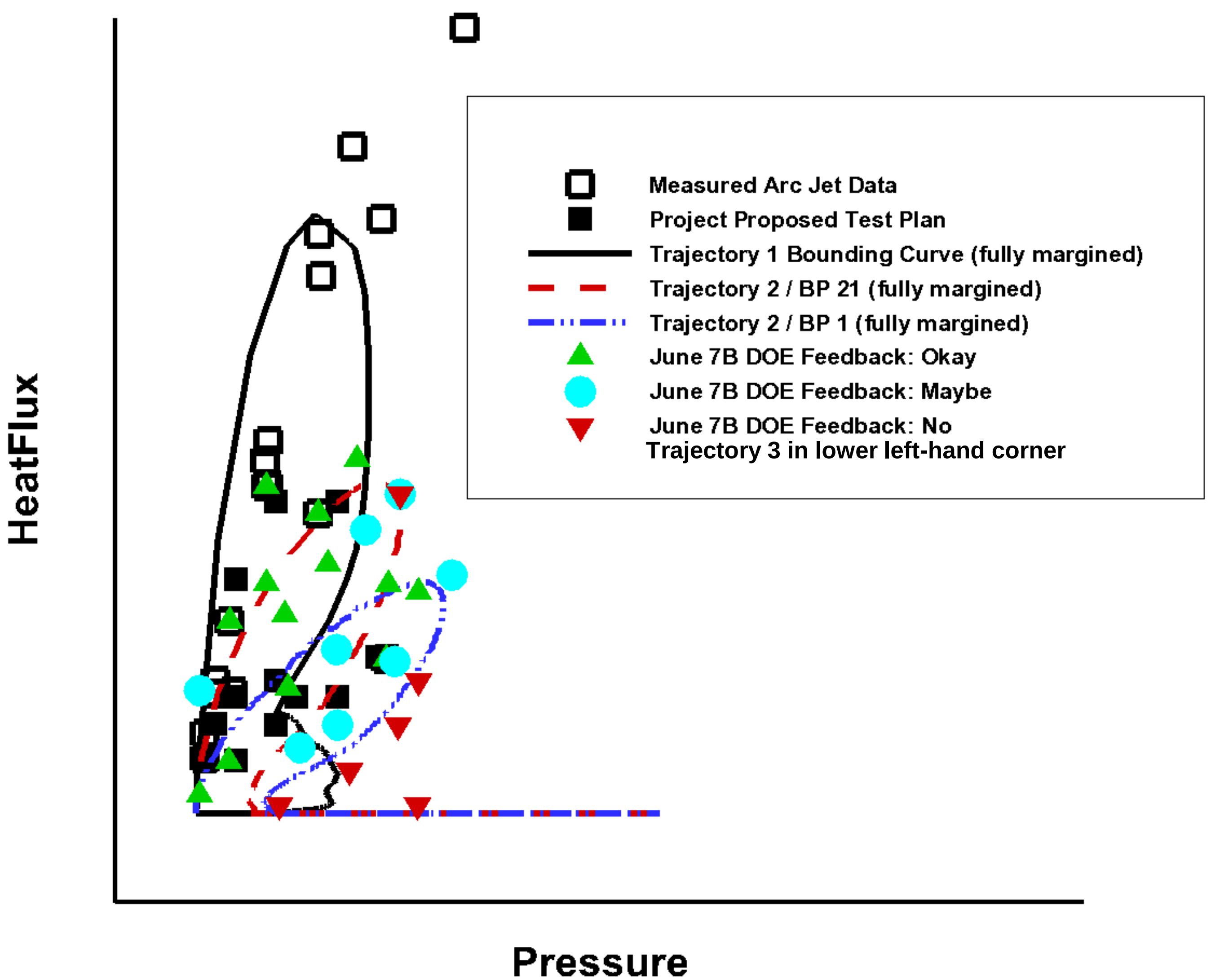
Existing data is aligned with a high heat flux trajectory – not the primary current focus

Design Of Experiments (2)

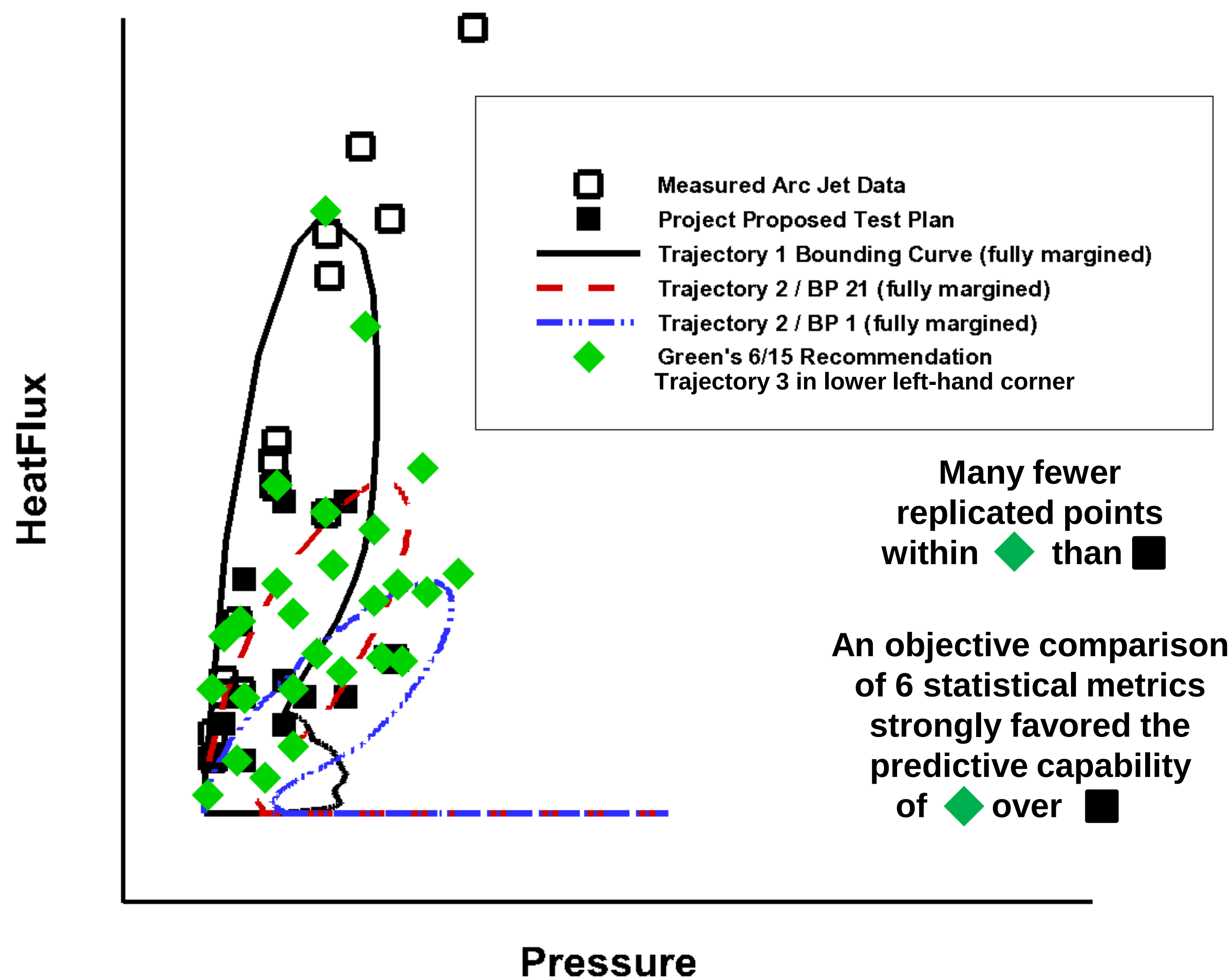


One or more repeats of each ■

Design Of Experiments (3)



Design Of Experiments (4)



Many fewer replicated points within ◆ than ■

An objective comparison of 6 statistical metrics strongly favored the predictive capability of ◆ over ■

Reliability Assessment Process

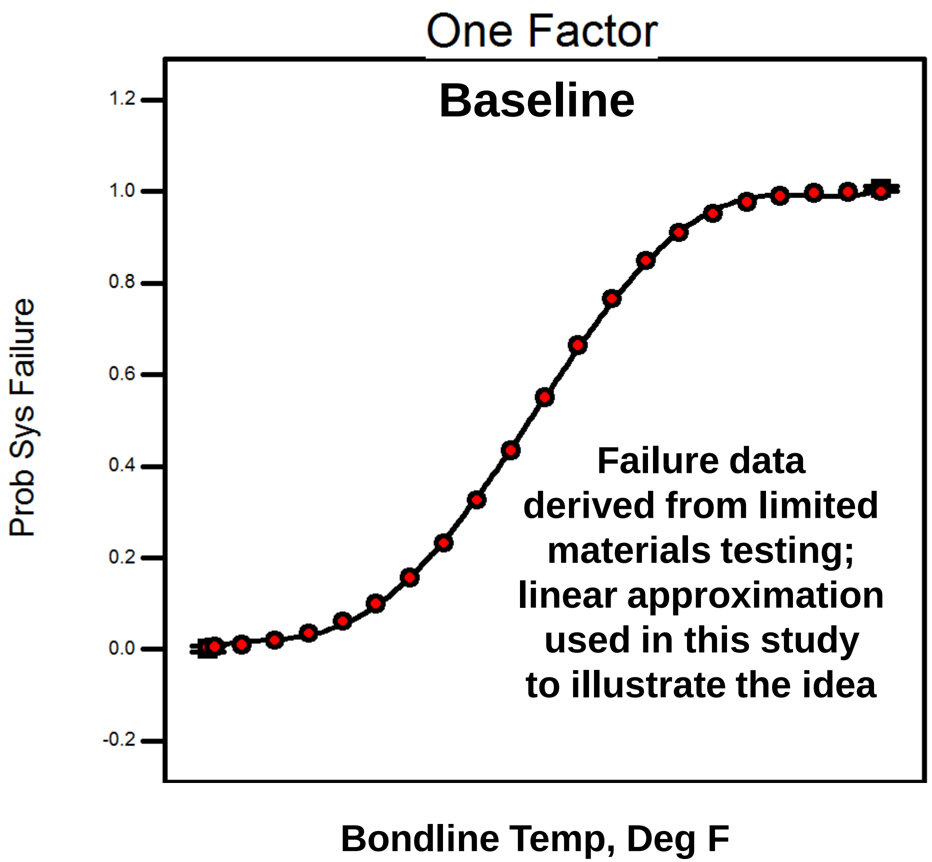
Reliability Assessment
Problem Formulation

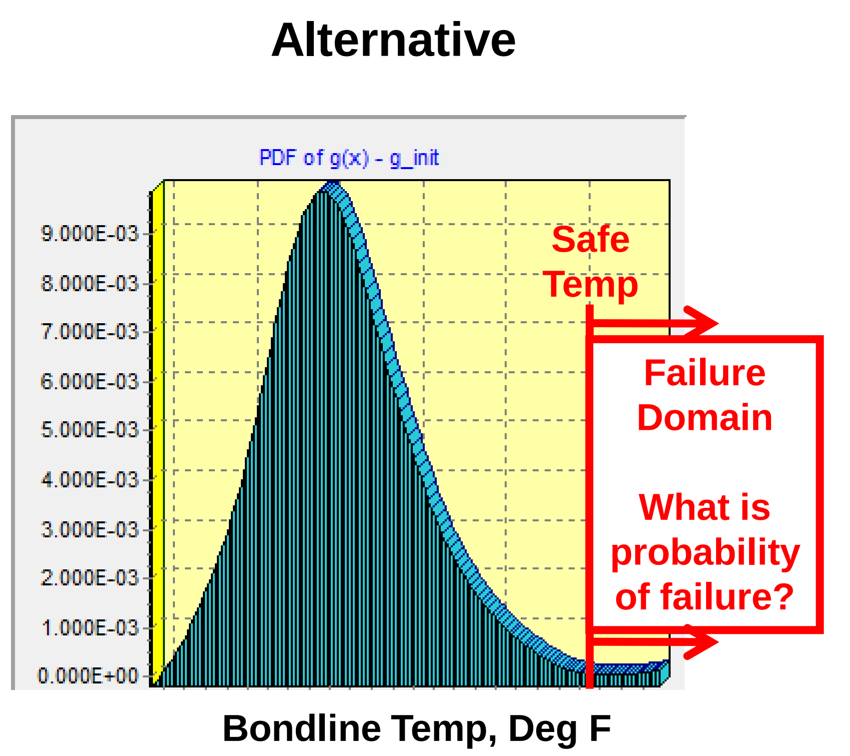
- The STAB computational model
- Presumed Safe Temp Limit
- Current heat shield design thickness and carrier structure
- Two trajectories analyzed (trajectories #2 and #3)
- Five heating environments, with various margining assumptions, were examined for each trajectory; these are bracketed by:
  - **Case 0 = Transitional heating**
  - **Case 3 = Trajectory dispersion and aeroheating uncertainty (fully turbulent)**
- Seven body points: one from each of the trajectory dispersion zones.
  - **The body points are 1, 15, 21, 102, 109, 161, and 229.**

70 Total Reliability Assessments:
2 trajectories X 5 environments X 7 body points

Reliability Assessment
Failure Criteria Formulation

- Baseline: system failure probability proportional to maximum multi-point exceedance of safe bondline temperature (UNIPASS)
- Alternative: joint multi-point probability of safe bondline temperature exceedance (UNIPASS and SPISE)

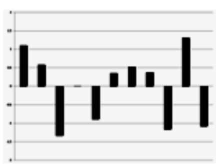




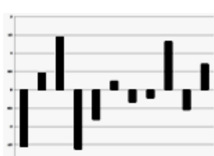
Reliability Assessment
Response Surface Generation

1000 case STAB
run template of
prescribed, random
departures from
nominal values
for 11 material
properties

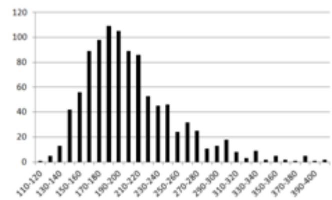
Select
reliability case
(70 possible)



.
.
.



Bounded distribution;
easy to implement

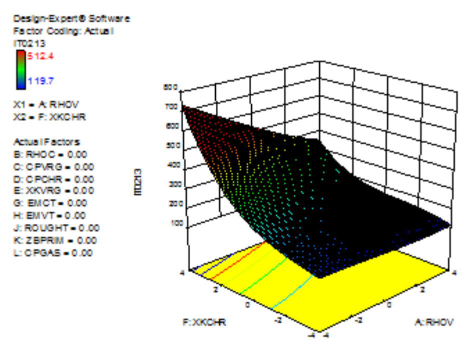


Btemp = Beta(MV, SD, XL, XU)
MV = mean value; SD = stdev
XL = lo bound; XU = hi bound
or, Btemp = Uniform[XL, XU]

lumped material properties

Implemented in
UNIPASS by Green
using MCS

Or



Btemp = f(X1, X2, … X11)
11-dimensional cubic RS

distinct material properties

Implemented
in SPISE by PPI
using FORM

During RS interrogation,
the material property variations
can be treated as correlated or not

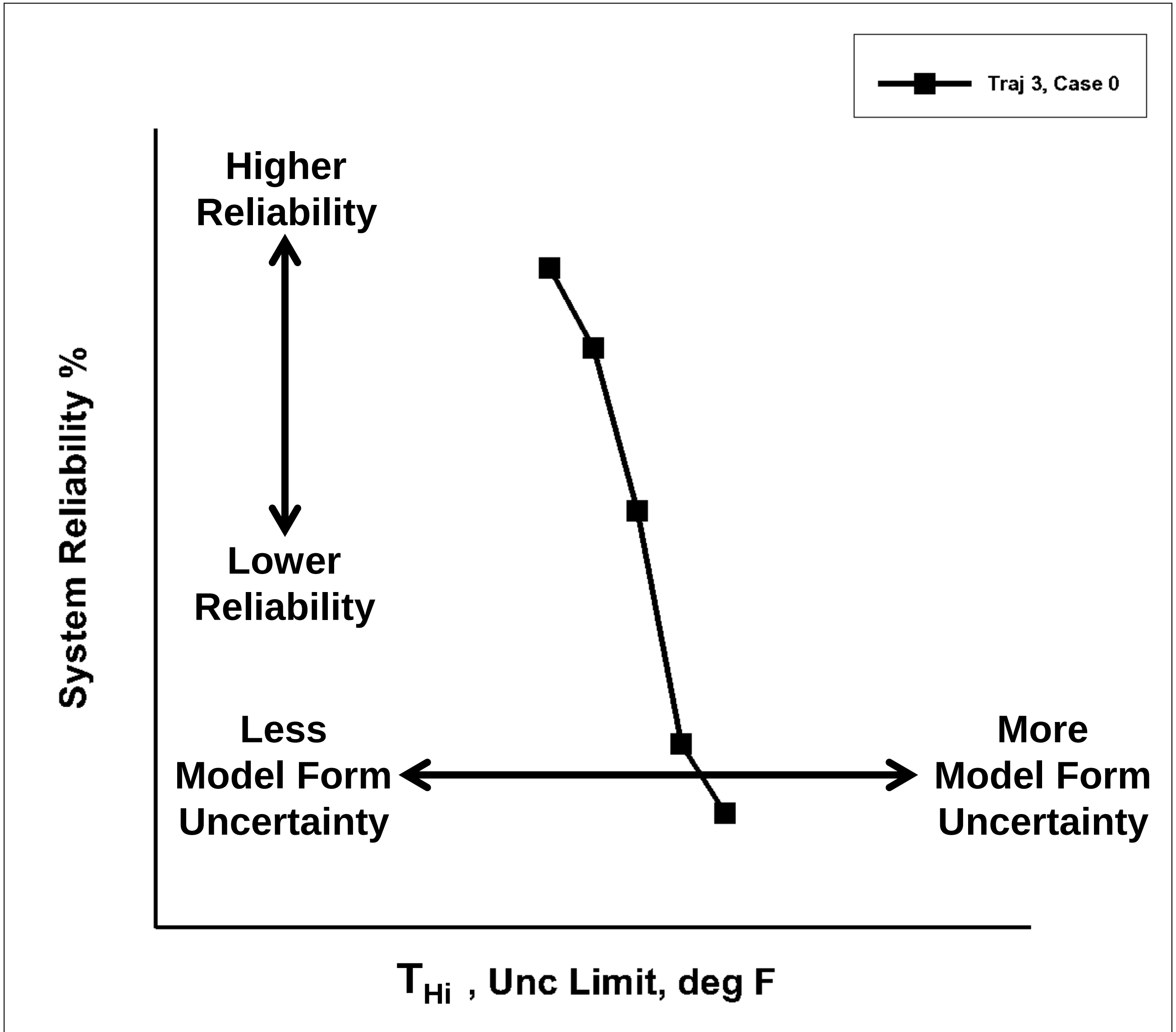
Reliability Assessment
Reliability Assessment Process

3 Nested loops:

1. Outermost loop: problem setup
   - **Select “safe” bond line temperature**
   - **Select the exact form of the reliability formulation:**
     - **Material property variation RS form**
     - **Failure constraint**
     - **Number of MCS samples**
     - **Confidence level, convergence tolerances, etc.**
2. Intermediate loop: select **user input** value of T_{Hi}
   - **Upper bound of model form correction uncertainty term**
   - **Treat this term as a uniform distribution [T_{Lo}, T_{Hi}]**
3. Innermost loop: conduct **reliability assessment** subject to **material property variations** (11-D cubic, or 1-D Beta / Uniform RS) with
   - **Added model form correction uncertainty term from loop 2**
   - **Failure constraint associated with “safe” temperature from loop 1**

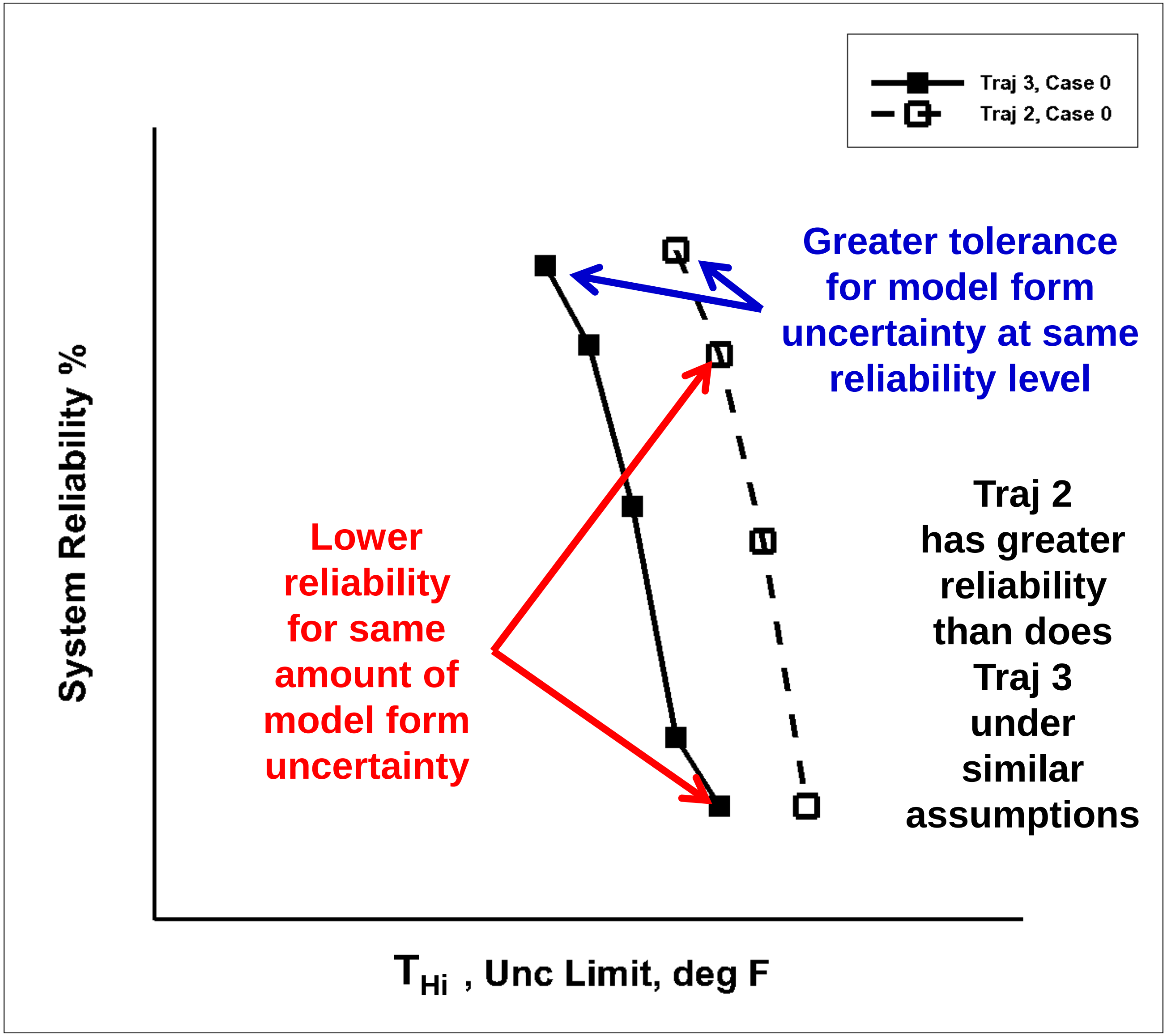
Reliability Assessment Results

Reliability Assessment
Trajectory 3, Case 0



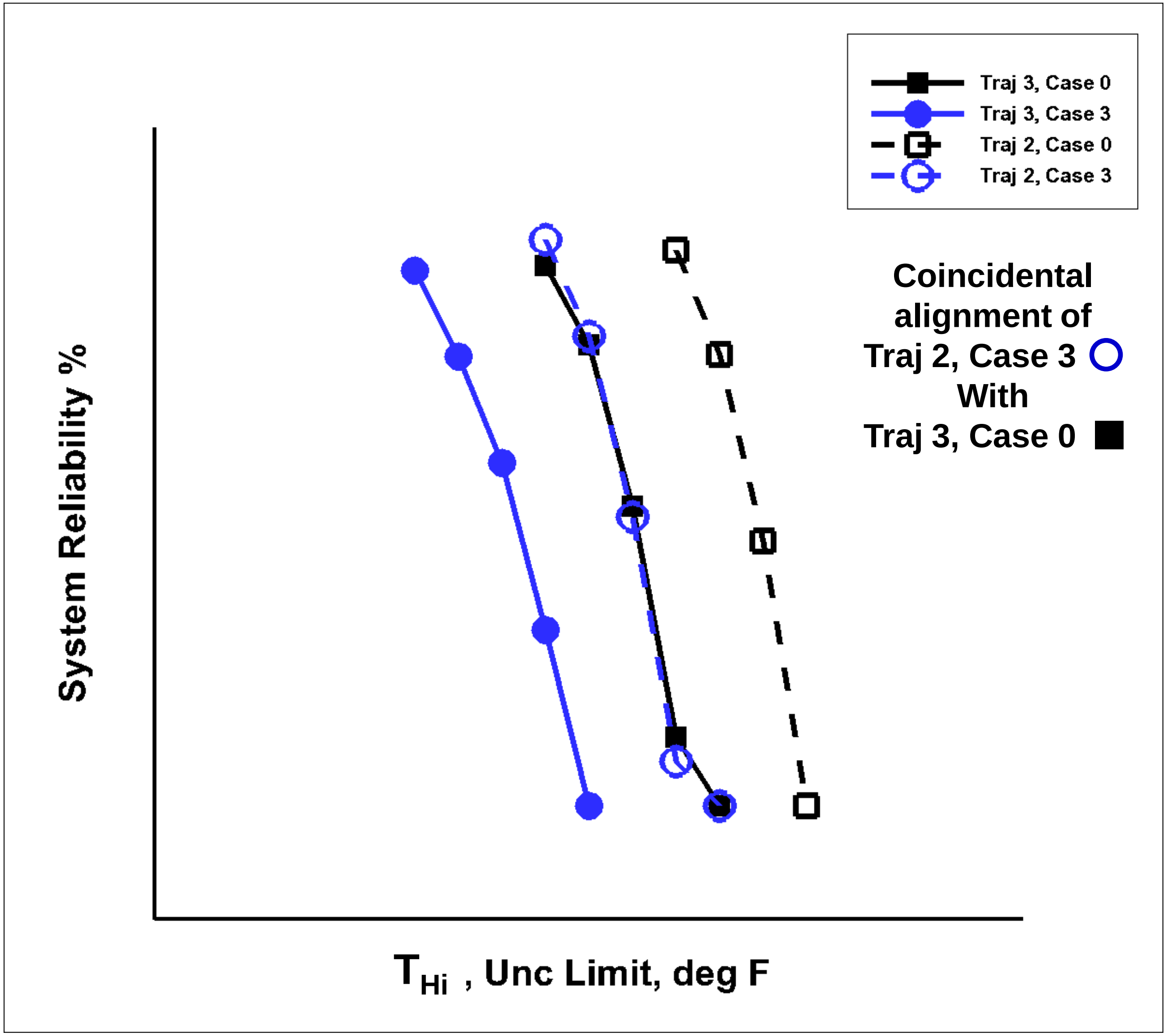
Reliability Assessment

Trajectory 2 and 3, Case 0



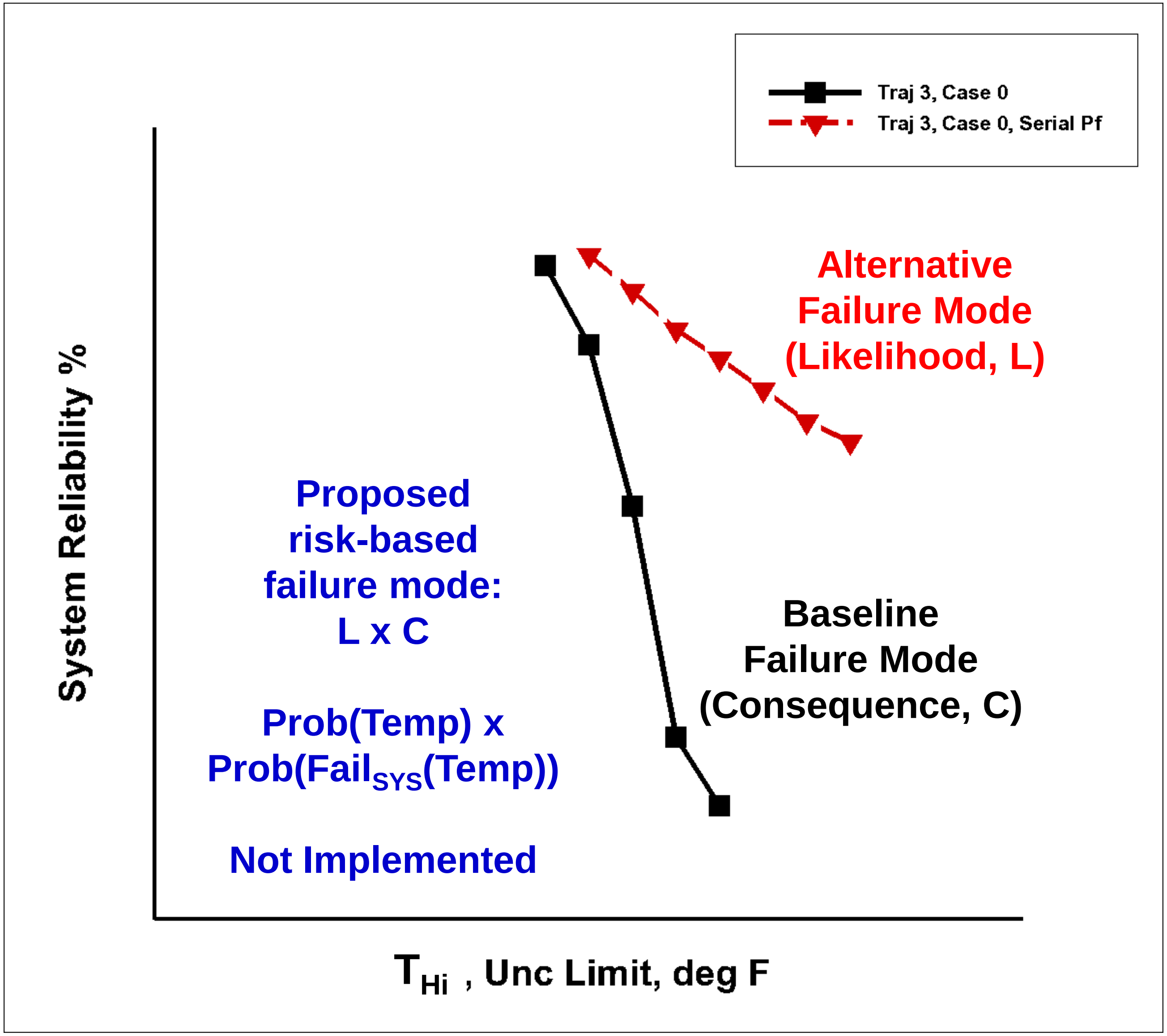
Reliability Assessment

Trajectory 2 and 3, Case 0 and 3



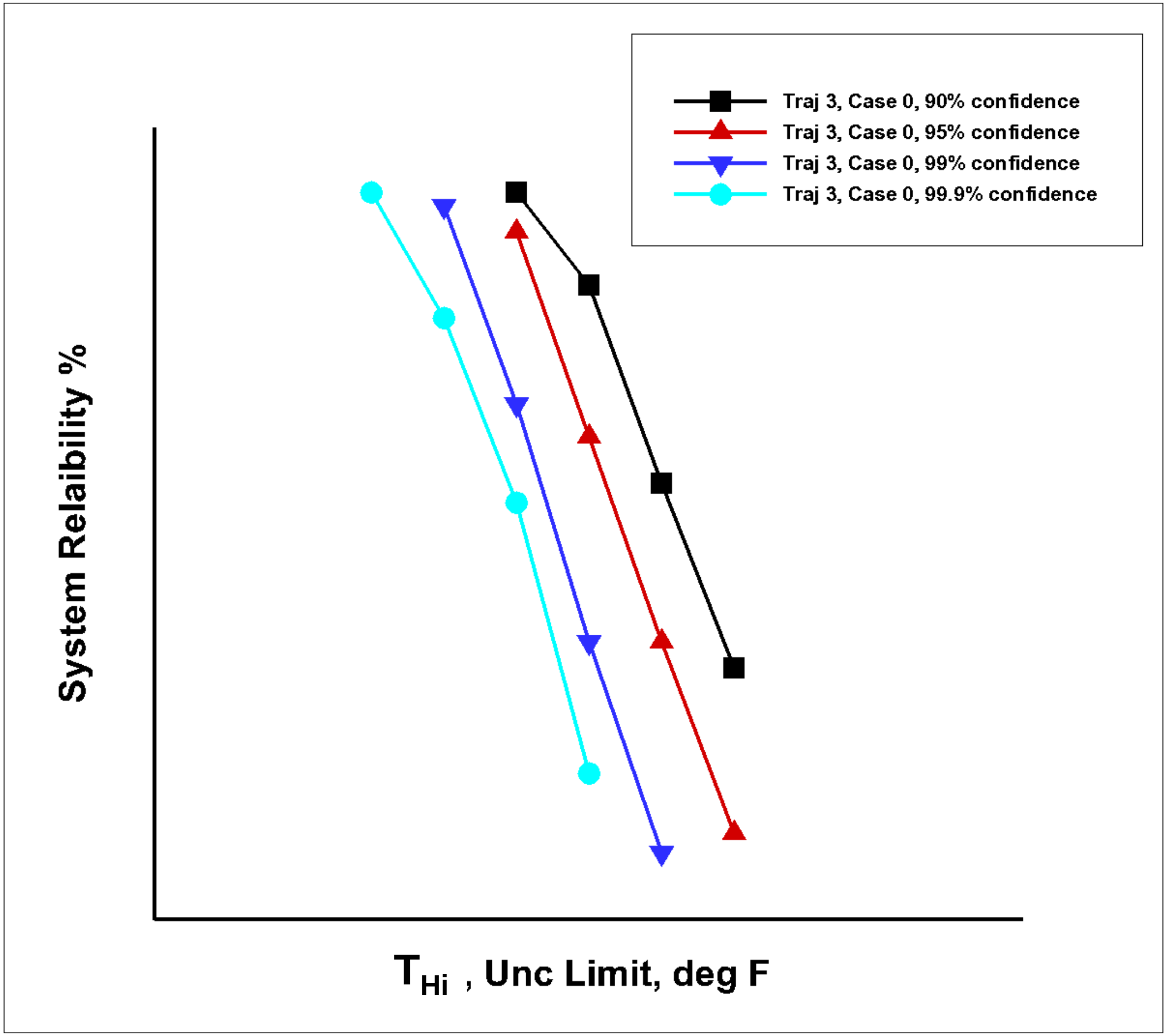
Reliability Assessment

Trajectory 3, Case 0, Different Failure Modes



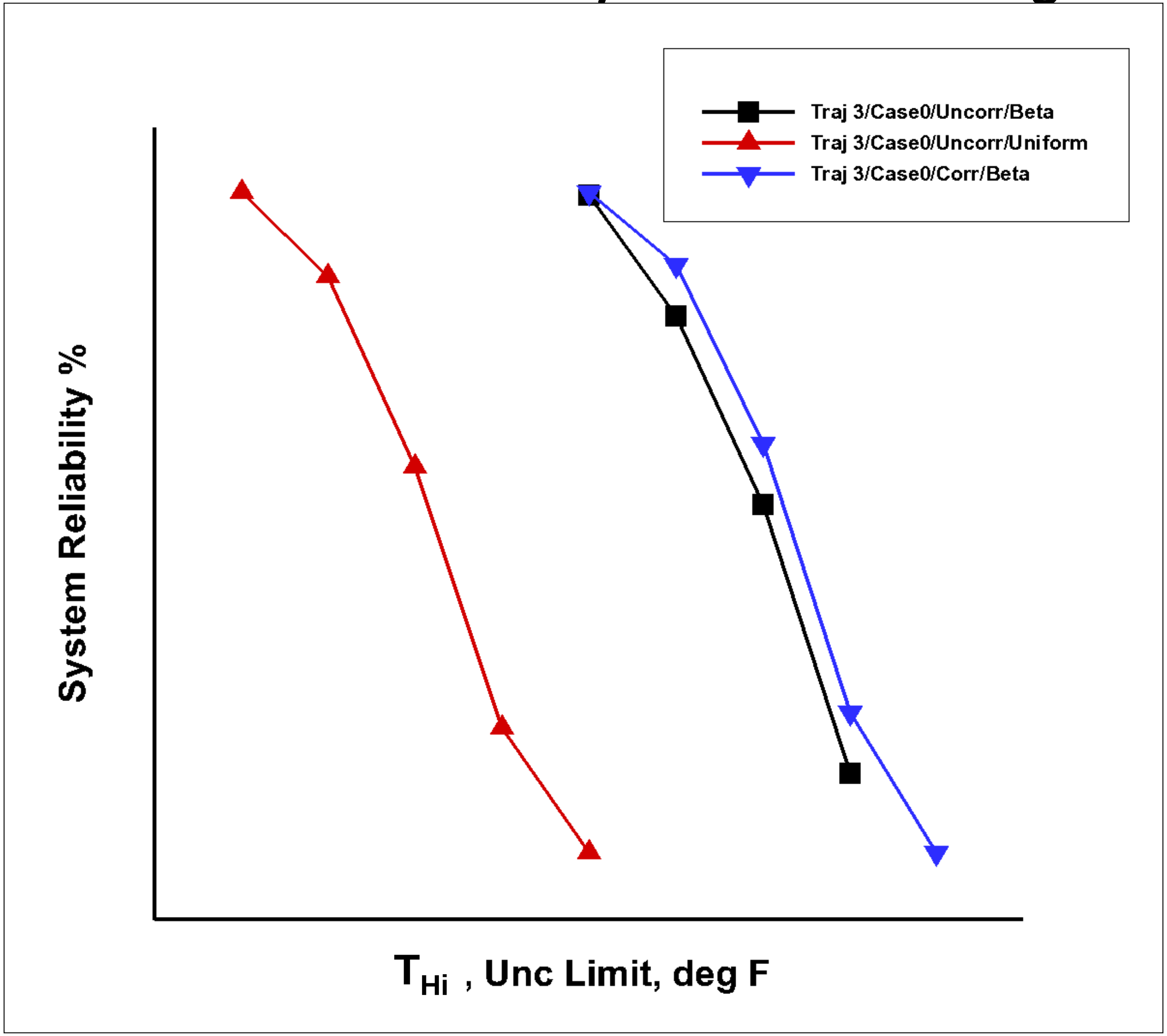
Reliability Assessment

Trajectory 3, Case 0, Effect of CDF Confidence Level, Baseline Failure Mode



Reliability Assessment

Trajectory 3, Case 0, Effect of Material Property Variations, Correlation and Beta/Uniform Modeling



Summary

- D-Optimal Design of Experiments for new arc jet testing campaign
- Reliability Assessment Formulation
  - Baseline:
    - **Model Form Uncertainty (Test – Computation) = Function of T_{Hi}**
    - **Two trajectories**
    - **Five heating environments**
    - **Seven body points**
  - Variants:
    - **Material property variation RS options (11-D cubic, 1-D Beta or Uniform distributions)**
    - **Probabilistic method (Monte Carlo Simulation or FORM)**
    - **Baseline or alternative failure criteria**
    - **Analysis platform (UNIPASS or SPISE)**
    - **Confidence level and body point correlation**

Study Closeout

- Key findings:
  - **Three sources of uncertainty within the system wide analysis were found to have a dominant effect on the reliability assessment**
  - **Different forms of the reliability assessment formulation yielded very different reliability assessment results**
  - **The DOE process for test planning resulted in a technically improved test matrix for the thermal response tests**

The End

Thank You!

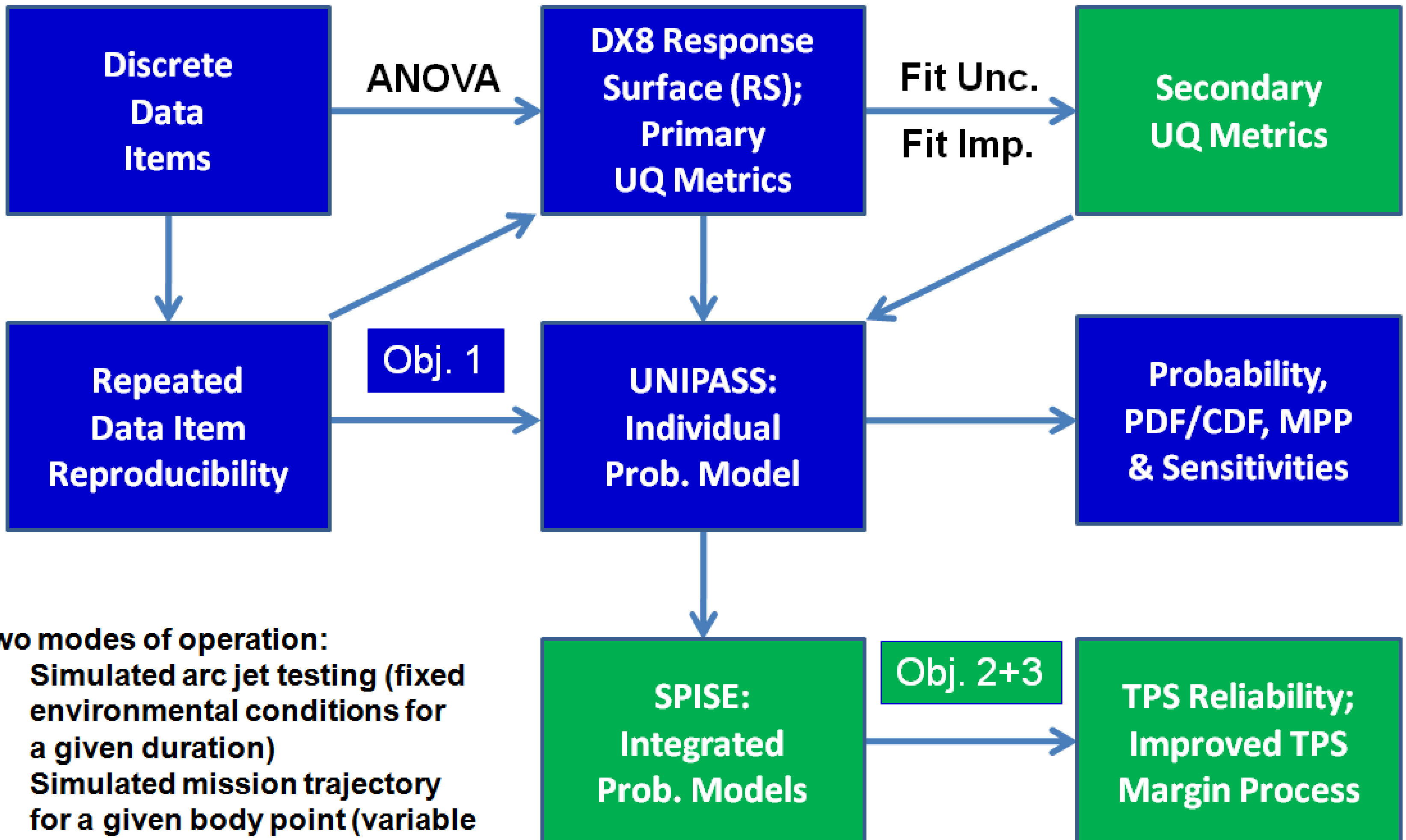
Back

Up

Charts

Introduction (8)

Notional Uncertainty Quantification Process



Two modes of operation:

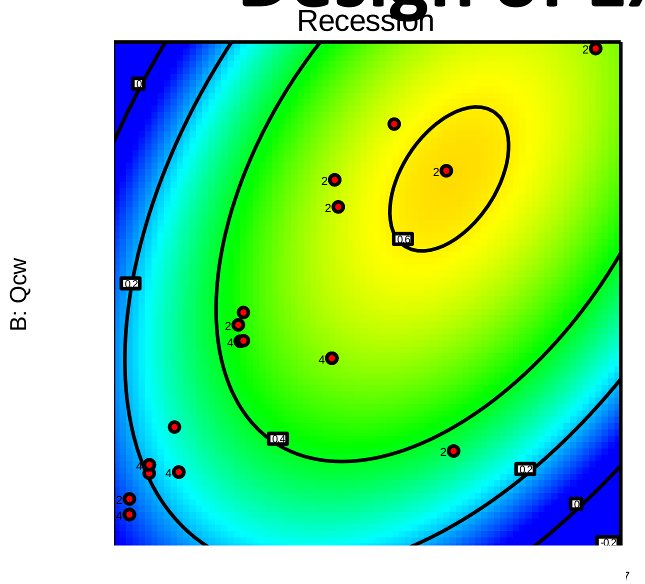
1. Simulated arc jet testing (fixed environmental conditions for a given duration)
2. Simulated mission trajectory for a given body point (variable environmental conditions)

Design of Experiments (5)

Design-Expert® Software
Factor Coding: Actual
Recession
● Design Points
0.763
0.07

X1 = A: P
X2 = B: Qcw

Original Data
(1)



Metric	(1)	(2)	(3)
StDev	0.0716	0.0515	0.0597
PRESS	0.2574	8.7359	3.7370
R-Sq	0.8980	0.9802	0.9832
Adj R-Sq	0.8788	0.9635	0.9699
Pred R-Sq	0.8397	-0.8969	0.5404
Adeq Prec	19.9239	42.9057	51.6837

Average metrics over 10 samples

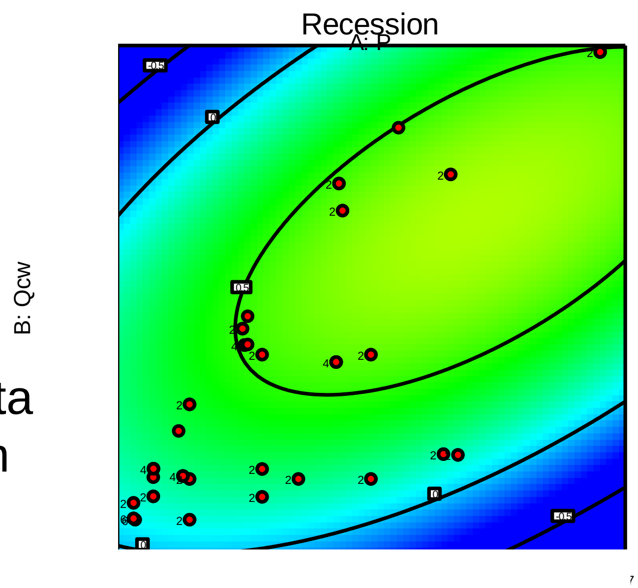
Highlights show the better of the two metrics

Rec = Rec(P, Qcw); Dur dependence ignored here for the sake of illustration

Design-Expert® Software
Factor Coding: Actual
Recession
● Design Points
1.16814
-0.297814

X1 = A: P
X2 = B: Qcw

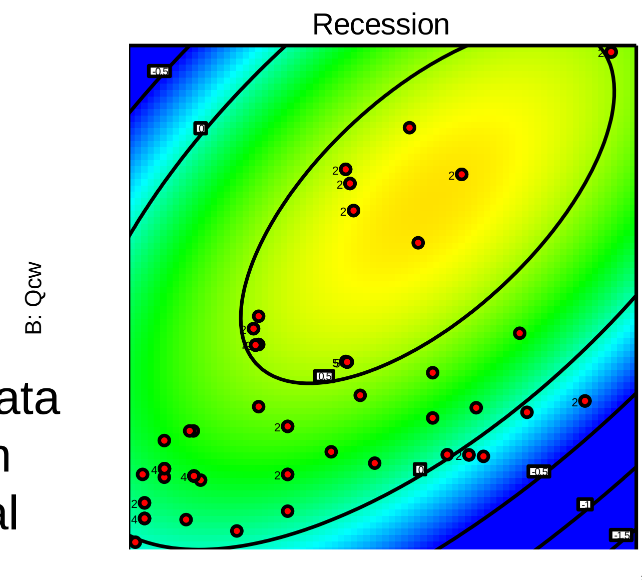
Original data
\+ Program
Proposal
(2)



Design-Expert® Software
Factor Coding: Actual
Recession
● Design Points
1.01411
-0.48204

X1 = A: P
X2 = B: Qcw

Original data
\+ Green
Proposal
(3)



Reliability Assessment

Reliability Cases

Margining Process Case Identifier	Description
0	No trajectory dispersion, no aerothermal margin, transitional heating
1	No trajectory dispersion, no aerothermal margin, fully turbulent
2	No trajectory dispersion, aerothermal uncertainty, fully turbulent
3	Trajectory dispersion, aerothermal uncertainty, fully turbulent
4	Trajectory dispersion, no aerothermal uncertainty, fully turbulent

"Best Estimate" Trajectory

Bracket the results

"Fully Margined" Trajectory

Reliability Assessment

Reliability Assessment Process Illustration